Research on the Behavior Process Oriented Accident Modeling Technique for Complex System

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Abstract

The complex system has the features of high complexity of behaviour process, diversity of operational environment and multi-factor coupling of human, equipment and environment, which brings huge challenge to the safety assessment. Through analysing the domestic and foreign accident-causing theories and accident modelling methods, the current study result and their deficiencies are revealed, and on the basis of the accident characteristic analysis of behaviour process of complex system, multi-view based behaviour process accident modelling method for complex system is proposed. Through modelling analysis, the factors causing the accident, combination of these factors and evolution path of accident are analysed and then the safety state space of complex system to realize the precaution and control of accident is established. Finally, through case study, the applicability of this method is verified.

Keywords

Accident Modelling; Safety; Behaviour Process; Aircraft

Preface

As system becomes increasingly complex, the occurrence of system accident and the accident process show strong multi-factor coupling characteristics. The slight change of initial condition and different combinations of various factors will lead to different behaviours. Human behaviours in the behaviour process naturally will stimulate different combination features and bring about complicated system accident evolution processes through various forms of coupling of mutual interaction, mutual supplementation and mutual restriction among operational environment, hardware system and software system in the field of material, energy and information.

Regarding exploring the law of accident occurrence, there are many domestic and foreign accident-causing theories, among them he STAMP-system attribution model proposed by Nancy Leveson of MIT is a typical representative of the final stage of accident modelling development. People all believe that during the evolution of accident, the fixed sequence of accidents does not exist. Within certain range of space-time, there exists interactive-factor such as human, equipment and environment, there will be accident. However, the theory put forward by Nancy covers the aspects of management and humanity, without giving a specific and strongly practicable modelling and analysis method.

Traditional safety analysis method depends too much on personal experience; methods such as FTA and ETA analyse the known logical relationship between cause and effect of accident process. In the respect of methods are used to safety simulation, comprehensive researches have been carried out home and abroad, particular in the field of human factors and human decision-making models and human recognition process models have been provided. With regard to simulation analysis of accident process, one hand the Petri net and finite state equipment are applied to the analyses of flight process of commercial aircraft and contingency plan as a quantitative analysis conducted on the basis of a known accident processes; on the other hand, the effects of hardware failure modes on the safety of equipment are analyzed at the mechanism angle and the model-based safety analysis method is proposed.

Currently, there are few studies which are preceded

from studying the complex coupling relations of multiple factors, and can provide modelling method for clearly and completely reasoning the evolution process of accident. In the view of the situation based upon multi-view and complex system behaviour process, an accident modelling method is proposed for accident causing factors, combination for these factors and accident evolution path, and under the effects of certain factors and the combination of factors, whether the system will have an accident, and then establishing the safe state space of complex system. Through case study, the applicability of this method is verified.

Accident Evolution Process of Complex System

During the operation of systems, the occurrence and development of accident has a close relation, with the hierarchical structure, sequential logic relationship among activities and system state of system behaviour process. Failure cause is reflected in the components of system and its state, that is, unsafe human behaviour, unsafe substance condition, unsafe environment state, even management failure and their interrelations and interactions. Due to human error, equipment failure and environment change, the output will change correspondingly. Operator will adjust system state through output feedback, and the equipment will have certain self-adaptive function as well. When system state goes beyond safety limit, system will then be in a dangerous state, i.e. without effective control, there will be an accident. Complex system accident has the following features:

Dynamic

From safety to danger, from danger to accident, system state is in a dynamic changing process, changing with the continuously interacting among human, equipment and environment.

Process-oriented

From occurrence and development to accident, the process shows characteristics of time delay of development and secondary effect of events before accident occurrence.

Uncertain

All the elements affecting system safety, such as human operation, equipment failure and environment change are uncertain, and make the evolution of the system state form being in safe state to being accident state.

Multi-factor coupling

During the operation of system, the human, equipment and environment are in the same loop, and due to human error, equipment failure or environment change, the output will be changed correspondingly. So the occurrence of accident is closely related to the coupling characteristic of subsystem failures in the system.

The state space of the evolution of system state during operation can be divided into safe space, hazard state space and accident state space (the latter two can be jointly called unsafe state space). State margin is the dividing line between safe and unsafe state space. Safety margin is also the watershed of safety control. Specifying the evolution path of system accident and establishing system safety margin are of significant importance. Accident evolution process is shown in figure 1.

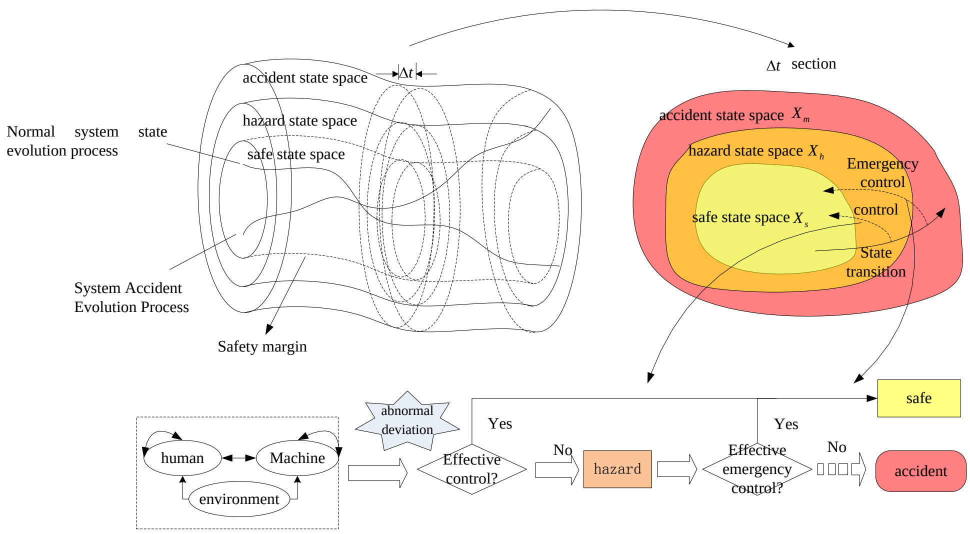

FIG. 1 EVOLUTION PROCESS OF ACCIDENT

Multi-view Based Accident Modeling Method for the Behavior Process of Complex System

Multi-view Based Accident Rehearsal Modelling Process

1) Connotation of Accident Rehearsal

Definition of accident rehearsal: is defined as through the description of coupling relation and interaction of various factors such as human, equipment and environment involved in system operation, and the simulation of system operation, starting with initial cause which affects safety of system operation, and rehearse under the effect of certain factors and their combination, whether the system will have an accident, on the basis of which establish complex system safety state space.

2) Connotation of Multi-view

During modelling and simulation, multi-view includes three categories:

a) Event view

Event view aims at complex system structure and functional hierarchy, performs top-down decomposition and abstract description of hierarchy between events (activities) which form behaviour process and their subordinating relationship; then on such basis, specify various factors involved in each activity of behaviour process (such as pilot, airplane, environment, etc.), as well as parameter reference and constraint criterion of accident modelling and simulation on the basis of the property of various factors and their range, such as delay time by pilot, operation type; speed, altitude and pitch angle of airplane; environment type and so on.

b) State View

State view describes the states of human, equipment and environment possibly existing in activity unit of behaviour process, and the trigger condition of state transition. For example, the pilot’s state can be normal operation or operation error, and environment effect and equipment failure could trigger the operational error.

c) Process View

Process view describes temporal logic association among events (activities) which form the flow, and flow process. Temporal logic association is driven by activities (for example, an activity is initiated when the corresponding activity arrives). Therefore, the basic unit of process view is activity. In terms of expression form, temporal logic view combines activity view and all the activities within state view to describe the operating mechanism of flow, and establish the dynamic description of process.

3) Multi-views based Accident Rehearsal Process

Above all, accident rehearsal process on the basis of multi-view conduct in-depth analysis of system and system task, including system function, system hierarchy, system operating principle, system failure, description of behaviour process, factors affecting safety involved in stages and behavior process and the relation among factors.

On that basis, centering on process chart, beginning with the starting point of object process (for example, begin to describe with interception of glide path when describing airplane approach), the selection of activity path during the process depends on system real-time status in state view. Meanwhile, different human operations, environment, equipment types and conditions determined by different activities also have different effects on system state. Through iterative interaction between process view and state view, the evolution process of system behaviour is simulated. At any point of time of evolution process, through abnormal deviation of human, equipment and environment caused by state view (such as personnel error, equipment failure, accident environment, etc.) describe modelling, inject deviation, rehearse evolution of system state under the effect of abnormal deviation of human, equipment and environment. According to constraint criterion determined by activity view, decide whether there is an accident.

Multi-view based Accident rehearsal modelling process is shown in figure 2.

Event View Based Process Hierarchy Model

Complex behaviour process is divided into object dimension and process dimension. The evolution of system state in the process is the process of the object dimension coupling in the process dimension. From two angles of object dimension and process dimension, in activity view, perform top-down decomposition and abstract description of hierarchy between events (activities) which form behaviour process and their affiliation, as shown in figure 3.

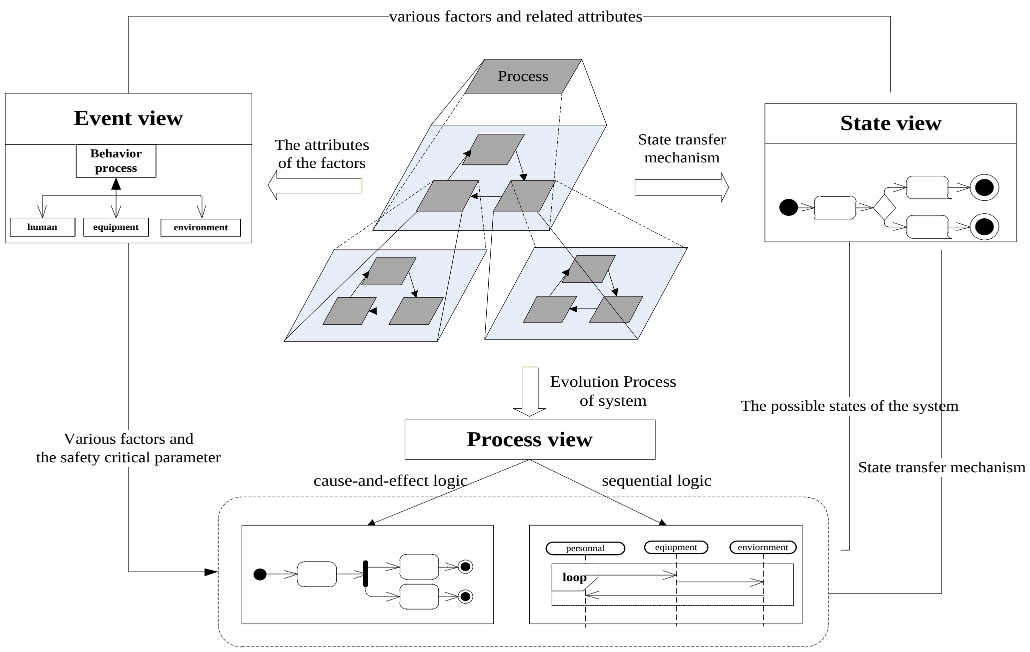

FIG.2 MULTI-VIEW BASED MODELING PROCESS

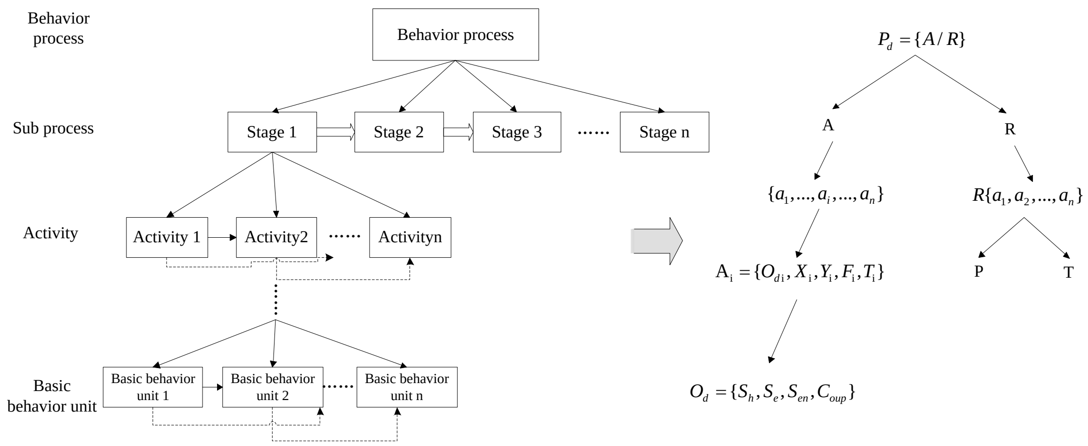

FIG. 3 SCHEMATIC DIAGRAM OF EVENT VIEW

The formal description of behaviour process: $P = < O_d, P_d >$

Where, O_d represents objection dimension, including human (operator, designer etc.), equipment (hardware, software etc.) and environment (weather condition, geographical condition etc.). $O_d = \{S_h, S_e, S_{en}, C_{oup}\}$; S_h represents personnel state; S_e represents equipment state; S_{en} represents environment state; C_{oup} represents the coupling of human, equipment and environment.

P_d represents process dimension, $P_d = \{A/R\}$. $A = \{a_1, a_2, ..., a_n\}$ represents collection of all the activities (basic behaviour unit) in process; $R = R\{a_1, a_2, ..., a_n\}$ represents all the relationships among activities.

Considering overall task as object, features of behaviour stage as basis, the breakdown of behaviour process is performed. The event view can be successively divided into several levels, i.e. from its top level of sub process, and then break down to its lowest level of basic behaviour unit. In order to differ from information transfer activity between personnel, the event (activity) here mainly means the common name of all the activities performed by personnel to change system state directly.

The principle of process breakdown is shown as follows:

- Limitation. Process cannot be decomposed without limitation. Either decomposed into sub-process or basic activity, there is always a principle on degree, that is, either the activity being decomposed or

sub-process must be meaningful.

- Determinacy. When decomposing behaviour process, the basic unit we have obtained must have determined input, output (result) and corresponding operation.
- Induction. If input or output of certain process is not well-known, we can consider it as a series of activities mutually related, and bring it into the previous process, rather than a single process.

Decompose all the factors such as personnel, equipment, environment involved in behaviour process. Combine features of all the factors to decompose involved personnel above basic behaviour unit, such as operator, maintainer and manager; involved equipments during operation, and their state, such as landing gear and flap of airplane; together with environment, such as wind shear, convective, heavy fog and rain. Finally, fill analysis result into table 1 to support multi-factor coupling analysis.

TABLE 1 EVENT-FACTOR ANALYSIS

	Layer		
factor / Basic unit	personnel	equipment	environment

As for each feature of human, equipment and environment which are involved in system, it is necessary to specify safety key parameters C_s determined by system itself, such as reaction time of personnel, diffusion range and time of the equipment on fire, radiation range of the radioactive equipment.

Establish safety key parameter set $C_s = \{C_{s1}, C_{s2}, ..., C_{sn}\}$, and fill it into table 2:

TABLE 2 KEY PARAMETER CONSTRAINT LIST

Parameters / type		C_{s1}	C_{s2}	……	C_{sn}
Type of personnel	operator				
	communicator				
	…..				
Type of equipment	equipment 1				
	equipment 2				
	…..				
Type of environment	environment 1				
	environment 2				
	…..				

State View Based System State Modeling

Taking the basic activity unit of system operation process analysis output as entry point, state view combines conclusion of single factor analysis on the basis of each basic activity unit, then deduces system output state determined by input multi-factor state as well as multi-factor coupling effect. The output state here mainly means state of the equipment and personnel, because whether the system is safe or not is generally expressed by state of the equipment and personnel. Define state in each basic activity unit A_i as a five factor group $S_i = \{O_{di}, X_i, Y_i, F_i, Q_i\}$.

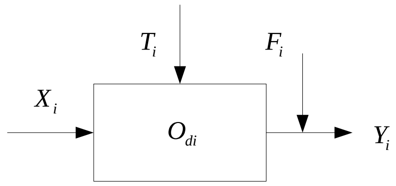

FIG. 4 A FIVE-FACTOR GROUP

Where O_{di} represents system sate in the i th basic activity, for example, the flight is normal, while with a low altitude.

X_i Represents event input when on activity A_i, that is state variables output of the previous activity unit system.

Y_i Represents the output of basic activity unit, namely the physical quantity system needs to observe, such as altitude and speed of an airplane.

Q_i Represents the trigger event in basic activity unit, which effects system state, abnormal environment does damage to equipment and human error.

TABLE 3 COUPLING DEVIATION

Property	Coupling Deviation Description
function	Nothing occurs
	Another action occurs or partially repeats
	partial action only is performed
	wrong action is performed
control	Controlling action does not occur
	Unexpected action occurs
	Action is unfinished
	wrong action is performed
time	Unexpected command
	Action occurs before set time
	Action occurs after set time
	No action
information	No communication
	Confusion occurs as other voice appears accompanied with command
	Receive only partial command (possibly due to noise)
	Send wrong command or misunderstood
	Send more commands than regulated
spatial position	No space
	Space relatively large
	Space relatively small

In $Q = < F, P_m, P_l, P_p, t >$, F represents factors, $F = < F_h, F_{en}, F_{eq} >$ including human factor F_h

(including operator, manager, and monitor), environment factor F_{en} (low visibility, crosswind) and equipment factor F_{eq} . P_m represents abnormal deviation type of human, equipment and environment factors. Human, equipment and environment are mainly coupled in five aspects (spatial position, time, function, information and control) and then affect the change of system state, shown in table 3.

P_l represents deviation range, such as the range of operation delay (deviation) $[t_1, t_2]$, which shows operation delay is between t_1 and t_2 . P_p represents probability of occurrence.

F_i represents state transition function, that is $Y = F_1(O_{di}, Q)$, composes execution condition of state transition which contains mainly two kinds of method:

- Production method refers to a rule like IF A THEN B, of which A is called as the left part or front part of the production, while B is called the right part or back part. The reasoning of production rule is based upon expert knowledge and visual experience.
- Analytic method. When input and output can be described by determined function relation, analytic method can be applied to directly describe logic relation among inner system (coupling relation among each sub-system), that is, to perform multi-factor coupling analysis through establishment of mathematic model and mechanical model.

t represents the time point when deviation occurs during the process.

Process View Based Process Logic Modelling

On the basis of process breakdown, apply process view method to describe the temporal logic association among events (activities) which form the circulation, as well as circulating process. Interactive relationship among activities $R = R\{a_1, a_2, \ldots, a_n\}$, $R =< P, T >$, P represents information transition between activities, T represents control relation between activities.

Define activity A as a six-factor group: $A =< N, S, X, Y, T, C >$, where

N represents activity name.

S represents activity state, S= {Normal, Abnormal}, of which normal states include: waiting, preparation, operation, cancel, complete. While abnormal states include: “abnormal start” and “abnormal stop”.

X, Y represents information flow transition between activities, X represents information input while Y represents information output;

T represents control flow relations among activities, typical control flow structures are shown in figure 5.

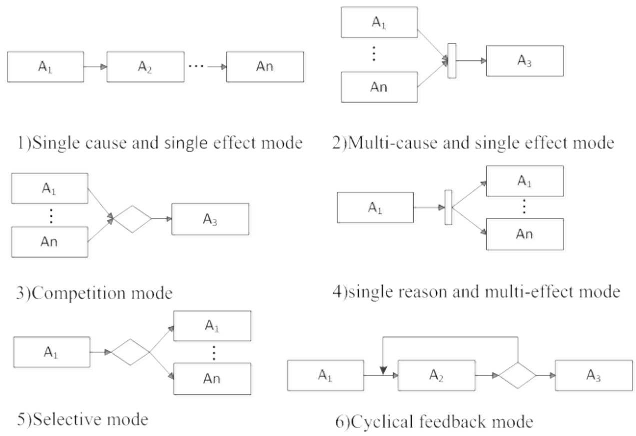

FIG. 5 CONTROL RELATIONS

1) Single cause and single effect mode: one cause and one reason mode refers to the secondary relationship between the simplest failures, that is one premise event lead to one effect event;

2) Multi-cause and single effect mode: multi-causes and one effect is to express the relationship of premise events with the relationship of “and”, that is, one effect event is triggered by several premise events, and only as these premise events occur can lead to effect event

3) Competition mode: competition mode is equivalent to express the relationship of premise events with the relationship of “or”, its nature lies in one effect event is triggered by one of the several premise events, therefore the relationship between premise events is “degraded competition”;

4) Single reason and multi-effect mode: one reason and multi-effects mode is used to describe the phenomenon of “one premise event, several effect events”;

5) Selective mode: one event can lead to several follow-up vents, but during each system operation, as long as one of these is caused, we can select system state;

6) Cyclical feedback mode: to describe necessarily repeated activity under certain condition.

C represents trigger mechanism of activity transition, on the one hand according to behavior process requirement; on the other hand, depending on state of inner activity system, especially when different activity route has to be selected due to different instantaneous states, entity state input is necessary then.

Accident Modeling and Simulation of Carrier-Based Aircraft Landing Process

This paper targets at the landing process of a foreign carrier-based aircraft. It considers three factors that influence landing: vertical height variation of the aircraft carrier 3s before landing; human error due to environment (such as at night), and the time when human error occurs.

Behavior Process Description

After having intercepted the glide path entrance, the pilot lowers the carrier aircraft down along the glide path with the aid of Fresnel Lens Optical Landing System, FLOLS, and keeps flight path angle at about -3.5°. FLOLS can send 5 layers of beams with different colors which parallel to the glide path, the orange beam in middle indicates ideal track. If the pilot sees orange beam, it means the aircraft is on the ideal track. Then, the carrier aircraft is under the condition where there exists complex air environment, besides natural wind field; there is turbulent flow which is aroused by movement of aircraft carrier, of which the most significant one is wake flow called "cocktail". Moreover, because of constant movement of the aircraft carrier deck, as there is a big movement, the tail can be raised up by 2m or so, which is possible to cause large landing deviation. These external factors bring about difficulty for the pilot to maintain gliding track and accurate landing. At this time, the landing signal officer on the aircraft carrier will various factors of deck movement, aircraft feature and pilot skills, and sends command to the pilot on the radio to require him to adjust flight state or wave off.

Multi-view Based Process Modelling

1) Event View Based Modelling

The landing process of carrier aircraft is complex, involving many factors which includes equipment: such as aircraft, arrester wire, Fresnel Lens Optical landing guidance system; personnel: pilot, landing command officer (LSO); environment: cross wind, rain, heavy fog and cocktail flow. The hierarchy modelling of landing process is shown as figure 6. As table 4 shows the landing location of carrier aircraft is constraint criterion of safety.

2) State View Based Modelling

During the landing of aircraft, safe state includes: enter landing attitude, appropriate altitude, successful landing, successful wave off; dangerous state includes: low altitude, high altitude, enter wave off state; accident state: crash the carrier into the sea, out of the runaway.

The trigger events Q_i affect the aircraft state, which includes personnel and environment. Specific value is shown table 5:

The function of aircraft state transition F_i is aircraft motion model. When the carrier aircraft is gliding into the carrier, its speed and track angle are essentially unchanged, thus aircraft motion model can apply perturbation linear equation:

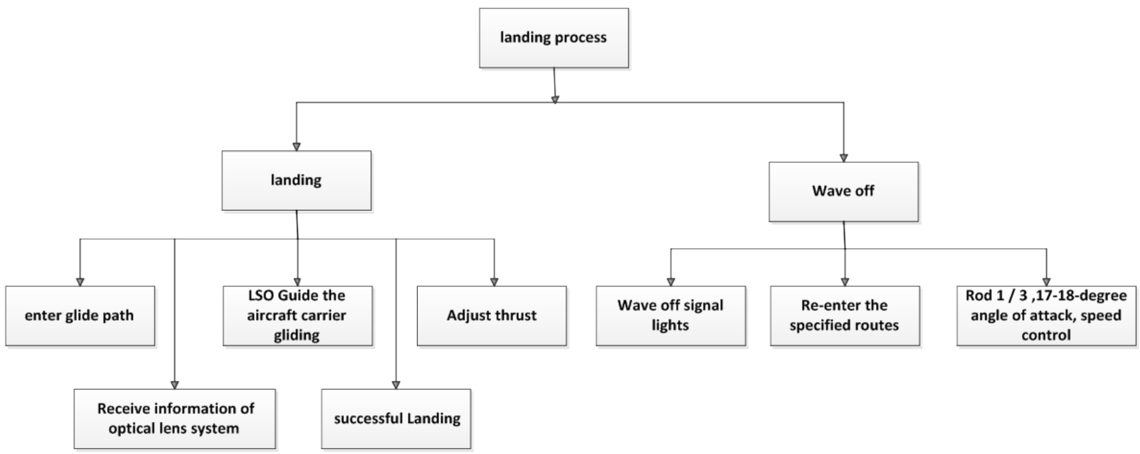

FIG. 6 EVENT VIEW BASED MODELING OF LANDING PROCESS

TABLE 4 ACCEPTABLE RANGE OF LANDING LOCATION DEVIATION (m)

Deviation type	Ideal value	Acceptable value
Horizontal deviation	-6.1—6.1	-12.2—12.2
Vertical deviation	-0.76—1.52	-1.52—3.05
Lateral deviation	-1.52—1.52	-3.05—3.05

TABLE 5 TRIGGER EVENTS

	F	P_m	P_l	t
Q_1	pilot	Perform wrong action	[-2,2]	[0，8s]
Q_2	deck	pitching	[-2.3，2.3]	3s before landing

$$\left.\begin{array}{l}\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\delta + \mathbf{E}\mathbf{w} \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\delta\end{array}\right\}$$

Where State vector $x = (v, \alpha, \vartheta, \omega_z, h)^T$; control vector $u = (\delta_z, \delta_p)^T$; output vector $y = (\theta, n_y, v, \alpha, \vartheta, \omega_z, h)$. Of which v represents disturbance quantity of carrier aircraft speed, m/s; α represents disturbance angle of attack, rad; ϑ represents disturbance pitch angle rad; ω_z represents disturbance pitch angle rate rad/s; h represents disturbance height variation, m; δ_z represents throttle lever deflection angle, rad; θ represents disturbance track angle, rad; n_y represents disturbance vertical overload, m/s^2 .

Besides Kinematics model of the aircraft, simulation involves other sub-model:

a) Pilot model. Apply variant strategy pilot model: if the carrier aircraft is affected only by small disturbance of wake flow, the pilot's operation of carrier aircraft is a constant tracking action; if the pilot is required to significantly change flight state, he will apply discrete control strategy.

b) Aircraft carrier air wake model. Apply marine atmosphere disturbance model defined in MIL-F-8785C, the speed components of which include free atmospheric turbulence component, steady component of aircraft carrier atmospheric wake flow, period component and random component.

c) Aircraft Carrier Motion Model. Apply engineered motion model that is simulate six -degree of freedom motion through harmonic form.

3) *Process View Based Modelling*

Based upon the description and analysis of the landing process of carrier aircraft, establish landing process view and specify the logic relationship of input and output between key activities. As shown in figure 7.

Result of Accident Modelling Simulation

This paper develops safety simulation of Carrier-based Aircraft landing process. Through simulation, we can rehearsal when these factors are combined with different values, whether Carrier-based Aircraft is able to land safely, then establish safety constraint model shown in figure 8. The space contained in the constraint figure is safe state space for safety, which composes dynamic safety constraint.

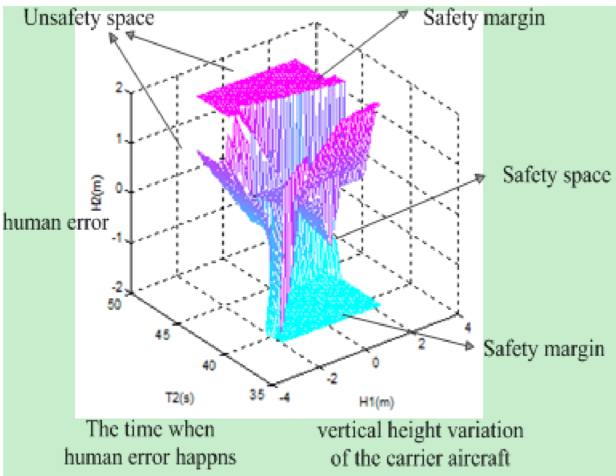

FIG. 8 SAFETY CONSTRAINT DIAGRAM

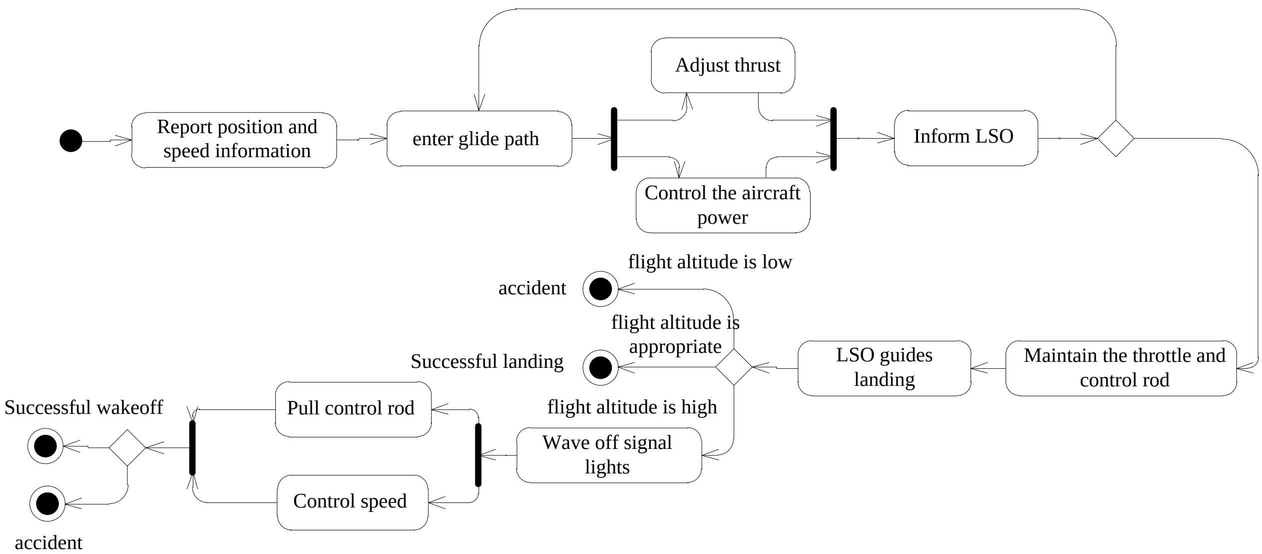

FIG.7 PROCESS VIEW OF CARRIER-BASED AIRCRAFT

Conclusion

The accident modeling method proposed in this paper emphasizes from multi-view angle to analyze the accident. Through event view and state view clearly interprets hierarchy and function relation in complex system process, temporal and logic relation among each activity, as well as coupling relation of human, equipment and environment involved in each activity. On this basis, through activity view, restore complex system process in order to develop safety analysis.

The multi-view based accident modeling for complex system provided by this paper aims for analyzing accident causing factors, combination for these factors and under the effects of certain factors and the combination of factors, whether the system will have an accident. Then we can establish the safe state space of complex system. Finally, through case study, the applicability of this method is verified.

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